SUPERCONDUCTORS

Superconductor Interfaces and Electrical Transport

Project Leader: Jack W. Ekin

Staff: 2.0 Professionals, 3.0 Students, 2.0 Technicians

Funding level: \$0.7 M

Funding sources: NIST (50%), Other Government Agencies (50%)

Objective: Develop measurement methods and obtain data for industry and for other projects within the Division in support of low-temperature and high-temperature superconductor applications in magnetics, power transmission, electronics, and microwaves. Characterize superconductor interfaces to aid in the commercial application of superconducting high current density wire and integrated circuits. Use unique measurement capabilities to develop transport and electromechanical measurement methods of the highest sensitivity and accuracy to assist industry in improving the performance of commercial thin films and wires.

Background: The high-temperature-superconductor (HTS) industry has asked for NIST's help to measure and develop high quality contacts and interfaces for both thin-film and bulk superconductor devices. The basic interface conduction mechanism is not yet understood. For example, recent data in our group has shown new evidence for magnetic scattering, which may have profound consequences for the theoretical understanding of the origin of HTS and formation of high-quality interfaces. In the magnet technology area, both HTS and low-temperature superconductor (LTS) magnets are being developed in the direction of larger magnets and higher fields (as for nuclear magnetic resonance); both directions lead to higher magnetic loading of the superconductor, which necessitates the need for measurements of the effect of stress on their electrical performance. The new HTS materials also have significant magnetic field anisotropy which has created a new set of measurement problems and modeling equations for conductor performance.

Current Tasks:

1. Develop metrology for characterization of electromechanical performance of superconductors and perform measurements needed by industry to create a database for commercial design of large superconductor magnet systems

FY 1994 Published chapter on electromechanical testing and modeling for book entitled *Composite Superconductors*; the critical J_c-B-strain surface, first discovered and modeled in our project group, was featured as the cover photo. Obtained first electromechanical data on a small *coil* of HTS bismuth conductor; these data and our accompanying interpretation were the basis for a U.S. company finding a superior epoxy system for their magnet fabrication. Measured and published the first data showing that the critical point in HTS bismuth-tape superconductor magnets will be at the ends of the magnet rather than at the high-field position in the middle as for low temperature superconducting magnets. Patents were filed by a U.S. company on new schemes for compensating for this effect.

FY 1995 Performed first very-high-field (23.5T) measurements of the effect of axial strain on critical current of experimental niobium-tin superconductor for use in the design of nuclear magnetic resonance superconductor applications. Measured effect of using dispersion hardened silver-magnesium-nickel sheath material on the irreversible strain limit of bismuth superconductors. Measured effect of reaction mandrel holder on prestrain and critical current of a niobium-tin candidate conductor for the International Thermonuclear Experimental Reactor design.

FY 1996 Developed technique for accurately measuring the Young's modulus of niobium-tin superconductors at cryogenic temperatures to resolve a long standing 300% discrepancy in values reported in the literature; Designed state of the art apparatus for measurement of the anisotropy of J_c with respect to magnetic field angle, for characterization of HTS at high currents in magnetic fields approaching 30 T.

FY 1997 Develop metrology for determining the effect of uniaxial strain on the critical temperature of bismuth superconductors; Complete construction and test angle apparatus for evaluation of bismuth superconductors at high magnetic fields; Measure the electromechanical properties of modern, practical niobium-aluminum superconductors; Measure the effect of fatigue degradation of high-purity aluminum in superconducting magnetic energy storage (SMES) magnet structures.

FY 1998 Measure the axial stress response of niobium-tin tape conductors for extending the strain Scaling Law from one dimension to three; Determine the relative importance of strain limits imposed on HTS coil structures by the superconductors vs. epoxy impregnation materials; Determine the effect of hot-isostatic-pressure (HIP) on the irreversible strain limit of niobium-tin conductors.

FY 1999 Measure the strain-scaling parameters for ternary niobium-tin superconductors; Develop metrology for electromechanical testing of magnet coil structures at elevated temperatures.

2. Develop metrology for evaluating superconductor interfaces and obtain database needed by industry for the development of high-quality electronic contacts and Josephson junction devices

FY 1991 First high-temperature superconductor contact patents issued to NIST: "Method for Making Low Resistivity Contacts To High-T_c Superconductors," and "High-T_c Superconductor Contact Unit Having Low Interface Resistivity, and Method of Making."

FY 1992 Third HTS contact patent awarded to NIST: "High-T_c Superconducting Unit Having Low Contact Surface Resistivity."

FY 1993 Performed a time exposure experiment for measuring the degradation rate of the yttrium-barium-copper oxide (YBCO) surfaces; results showed little effect of air exposure up to 100 minutes, much longer than expected; interface conductivity data showed little difference from *in situ* processed contacts, indicating that considerable improvement may be possible with *in situ* contacts. Fourth HTS contact patent awarded to NIST: "High-T_c Superconductor Contact Unit Having Low Interface Resistivity."

FY 1994	Measured the conductivity at the interface between a YBCO thin film and a silver contact, measurements covering five orders of magnitude of contact resistivity. Surprisingly, the transport characteristics of the interface indicated evidence for magnetic scattering over the entire conductivity range, indicating this may be a significant feature of HTS interfaces.
FY 1995	Performed an annealing study on a series of in-house-fabricated YBCO-silver contact interfaces to determine the effect of oxygen annealing on contact resistivity; Transferred the information to industry for optimizing the annealing conditions of *ex situ* contacts; Developed a new platinum-gold buffer layer for the integration of HTS and silicon-based contact systems.
FY 1996	Measured the 4 K, high-field (up to 12 T) tunneling characteristics of thallium interfaces fabricated at NIST using films from two manufacturers; Obtained the first high-magnetic-field tunneling conductance measurements of neodymium-cerium-copper-oxide films in collaboration with the University of Maryland; Discovered possible correlation between magnetic-field-dependent zero-bias conductance peak and evidence for d-wave pairing symmetry; Developed a method for improving the measurement sensitivity of our tunneling conductance measurements and obtained the first high-sensitivity transport properties of vertical a,b-axis superconductor/normal-metal junctions; Order-of-magnitude improvement over c-axis normal-metal interfaces achieved; Record specific resistivity of 2 x 10^{-9} ohm-cm^2 obtained for planar YBCO interfaces.
FY 1997	Measure annealing characteristic of YBCO/gold contact system and use the higher melting temperature of gold to determine whether the dominant improvement in contacts from oxygen annealing is oxygen diffusion or noble metal diffusion. Develop electromechanical test capability for thin-film interfaces. Extend the zero-bias-conductance measurements to fields of 18 T and to temperatures below the lambda point in YBCO, thallium-based, and neodymium-based junctions in order to discriminate between the Anderson-Applebaum and mid-gap resonant state models being proposed to describe the surface tunneling conduction of the oxide superconductors; Fabricate smaller a-axis junctions to determine the current-voltage characteristic to voltages beyond the gap voltage.
FY 1998	Develop method for nondestructively testing the mechanical strength of HTS wire bonds; Develop capability for precise noise measurements in thin-film junctions and measure noise characteristics as a function of junction area, voltage, temperature, and resistance; Develop *in situ* STM measurement system for conductivity mapping of HTS interfaces immediately after fabrication.
FY 1999	Develop model for characterizing noise in HTS superconductor interfaces for use in the engineering design of HTS bolometers and junctions; Develop submicrometer HTS interface test capability.

High Performance Sensors, Converters, and Mixers

Project Leader: Erich N. Grossman

Staff: 2.5 Professionals, 0.25 Technician

Funding level: $0.5 M

Funding sources: NIST (51%), Other Government Agencies (49%)

Objective: Develop electromagnetic field sensors and frequency converters for measurements and standards in support of other NIST divisions. Apply advanced superconducting integrated circuit fabrication, cryoelectronic, infrared, millimeter-wave, and other techniques to solve measurement problems at the limits of technology. Projects cover applications of Superconducting Quantum Interference Devices (SQUIDS), and in the infrared (IR), precise radiometry, frequency synthesis, spectroscopy, and imaging.

Background: The project represents the consolidation of previously separate efforts in mid- and far-infrared measurements and standards development on the one hand, and low-noise SQUID development on the other. The project now focusses more closely on infrared measurement technology. Mid- and far-infrared technology (wavelength >10 μm) is now a large industry. Originally aerospace and defense-related, it is now moving to many purely commercial applications in security, night vision, materials testing, quality assurance, and more. As such applications proliferate, supporting needs for measurements and standards technology are also increasing. Accurate measurement of total power and power spectral density (i.e., radiometry and low- resolution spectroscopy) is a recognized calibration problem for manufacturers of focal plane arrays and blackbody sources. This project, with the Radiometric Physics Division, develops precision radiometers for this type of measurement. Accurate measurement of coupling efficiency, both for conventional surface absorbers and for IR micro-antennas, is also a great concern to commercial and military developers of next-generation IR sensors. Finally, this project, together with the Time and Frequency Division, develops mixers for frequency synthesis and high resolution spectroscopy in the infrared. A number of applications, notably in wavelength-division multiplexed optical communication, require accurate measurement of very large frequency differences between two sources. The very high bandwidth of superconducting junctions naturally suggests them as candidates for such frequency metrology applications.

Current Tasks:

1. Develop absolute radiometer for the low background infrared (IR) facility (Radiometric Physics Division), for the measurement of light with a wavelength in the range of 10 micrometers

FY 1986	Concept of Kinetic Inductance Thermometer (KIT) developed.
FY 1990	Demonstrated closed-loop resolution of 1 picowatt using KIT without absorber.

FY 1993 KIT integrated with absorber which degraded resolution by more than a factor of 1000.
FY 1995 Dropped KIT in favor of transition-edge thermometer to improve manufacturing; Stabilized absorber to improve resolution; Demonstrated ability to fabricate transition-edge thermometers.
FY 1996 Delivered radiometer to Radiometric Physics Division, NIST.
FY 1997 Design and build second-generation radiometer with integrated blackbody source, demonstrating absolute accuracy of 0.1%.

2. Develop infrared antennas and diodes for solar power generation

FY 1995 Project begun with funding from Air Force; Collaboration with Time and Frequency Division, NIST, to develop accurate measurements of efficiency of infrared antennas and lithographic diodes.
FY 1996 Fabricated near-IR antenna using electron-beam lithography; Fabricated lithographic metal-insulator-metal diodes.
FY 1997 Continue development and IR testing of antennas and metal-insulator-metal diodes; Measure efficiency of each.

3. Develop infrared antennas and bolometers for focal plane arrays

(a) Room-temperature devices
FY 1990 Measured 50% coupling efficiency of lithographic spiral antenna to radiation in the 10 - 30 micrometer wavelength range.
FY 1993 Funding obtained through Idaho National Engineering Lab for antenna-coupled, 10-micrometer wavelength imaging arrays.
FY 1994 Measured significantly lower noise on ultrathin niobium microbolometers than on conventional bismuth bolometers (15 dB lower 1/f noise, {Noise Equivalent Power} NEP = 70 $pW/Hz^{1/2}$).
FY 1995 Measured cross-polarization rejection ratio for lithographic spiral antenna.
FY 1996 Completed task.

(b) Liquid-nitrogen-temperature devices
FY 1994 Measured (then) world-record low noise (NEP = 9 $pW/Hz^{1/2}$) on antenna-coupled, high temperature superconductor transition-edge microbolometer.
FY 1994 Began collaborative project on suspended, surface-absorbing transition-edge bolometers with a U.S. company.
FY 1995 Measured world record low noise level (NEP = 1.5 $pW/Hz^{1/2}$) on company bolometers.
FY 1996 Measured world record low noise level (NEP = 1.0 $pW/Hz^{1/2}$) on company bolometers; Demonstrated imaging capability in a small linear array. Task completed.

(c) Room-temperature antenna-coupled bolometers for imaging
FY 1996 CRADA established with Scientific Applications International Corporation (SAIC); Proposal for multimode antenna-coupled array developed.
FY 1997 Design, fabricate, and optically test room-temperature dipole antenna/bolometers for 10-micrometer detection and imaging.

4. Develop mixers for frequency synthesis

FY 1993	Measured world record large bandwidth (8 terahertz) on Josephson junction made from yttrium-barium-copper oxide via Shapiro steps.
FY 1994,95	Measured bandwidth of 27 gigahertz on Josephson junction made from yttrium-barium-copper oxide at a frequency of 30 terahertz via direct microwave intermediate frequency.
FY 1995	Developed optical fiber-coupled mixer block for Josephson junctions made from yttrium-barium-copper oxide and observed mixing between stabilized laser diodes operating at a wavelength of 780 nanometers.
FY 1996	Measured bandwidth of the mixing of the laser signals.
FY 1997	Measure harmonic mixing performance.

5. Develop SQUIDS for Gravity Probe B

FY 1995	Delivered complete DC SQUIDS to Stanford University for possible use in a satellite based experiment. Low-frequency noise (1.9 x 10^{-30} J/Hz at 0.1 Hz) was somewhat larger than expected.
FY 1996	Fabricated and delivered additional SQUID chips to Stanford University (with High-T_c Integrated Circuits Project). Task completed.

6. Develop AC/DC thermal converter

FY 1994	Initiated project to apply kinetic inductance thermometers to improve the accuracy at which alternating and direct voltage signals could be compared; Discussions held with collaborators in Electricity Division.
FY 1995	Performance analysis made of alternating and direct voltage converter using transition-edge thermometers.
FY 1996	Delivered chips and cryogenic mounts to Electricity Division; Performed preliminary alternating and direct voltage conversion measurements (with Electricity Division).
FY 1997	Provide improved chips and mounting assemblies to Electricity Division.

7. Wireless telecommunications at terahertz frequencies

FY 1996	Initiated program to develop antenna-coupled vanadium-oxide room-temperature bolometer.
FY 1997	Develop phase pattern metrology of lithographic antennas at frequencies of atmospheric absorption lines.

8. Develop multiplexed arrays of 100 millikelvin superconducting bolometers (with Nanoscale Cryoelectronics Project)

FY 1996	Wrote proposal to NASA, in collaboration with Goddard Space Flight Center.
FY 1997	Demonstrate SQUID multiplexing capability and measure NEP of bolometers with optical absorbers.

Josephson Array Development

Project Leader: Clark A. Hamilton

Staff: 3.00 Professionals, 0.5 Technician

Funding level: $0.9 M

Funding sources: NIST (55%), Other Government Agencies (45%)

Objective: Advance the sensitivity, accuracy, and speed of electronic measurement by developing Josephson array circuits and systems for such uses as programmable dc voltage standards, waveform synthesizers, and frequency sources. Support EEEL requirements for maintaining the national volt.

Background: Manufacturers of modern precision electronic components and instrumentation need intrinsic electrical standards at a level of accuracy above that achievable by traditional electrical metrology and artifact standards. The characterization and calibration of modern digital voltmeters, reference standards, and converters between analog and digital signals require the development of new and improved intrinsic standards for the measurement of voltage. Josephson array technology provides the means to meet these requirements. This project and its predecessors have revolutionized precision voltage measurement through the development of the world's first practical Josephson-junction array standards. Target customers are electronic instrument makers, DoD contractors, and national and military standards labs (Sandia, Army, Navy, Air Force). Superior electrical metrology has and will continue to enhance the competitive position of the U.S. electronics industry.

Current Tasks:

1. Develop dc Josephson standards operating at one volt and at ten volts

FY 1984	Theoretical and processing advances make one volt Josephson standards feasible.
FY 1985	One volt Josephson chip developed.
FY 1986	Josephson array adopted as basis for national volt.
FY 1987	Ten-volt Josephson chip developed.
FY 1989	First commercial one-volt Josephson voltage standard system (using NIST chips).
FY 1987-94	NIST supplies 176 chips to 36 national, military, and commercial standards laboratories in 20 different countries.
FY 1993	The program NISTVolt approved by NIST for distribution to other standards laboratories using NIST Josephson Voltage standard chips.
FY 1994	First production of Josephson array chips by U.S. company.
FY 1995	Development of compact Josephson voltage standard for Sandia/NASA begins.
FY 1996	Prototype of compact Josephson voltage standard delivered.

FY 1997 Add 4 K cryocooler to compact Josephson voltage standard to eliminate need for liquid helium. Develop compact Josephson voltage standard for DoE. Help organize and run 1997 National Conference of Standards Laboratories Josephson voltage standard interlaboratory comparison.

2. Develop programmable Josephson voltage standards

FY 1993 Concept of programmable Josephson standard developed.
FY 1994 Publication of concept and first experimental results.
FY 1995 First useful measurements made with programmable standard. High speed bias system developed. Superconductor-normal-superconductor junctions developed to improve programmable voltage standard.
FY 1996 High-accuracy sine wave synthesis with programmable Josephson voltage standard demonstrated; First direct check on thermal voltage converter; Patent on programmable JVS issued.
FY 1997 Demonstrate programmable JVS at output voltage greater than one volt.

3. Josephson Array Oscillators

FY 1990 Concept of phase-locked two-dimensional (2D) arrays developed.
FY 1991 Demonstrated first coherent emission from two-dimensional arrays.
FY 1992 Received U.S. patent for two-dimensional array oscillator invention; Characterized frequency response of oscillators.
FY 1994 Demonstrated off-chip oscillator emission from in the frequency range between 52 and 230 gigahertz; Measured record narrow (10 kilohertz) phase-locked oscillator linewidth; Completed stability analysis of 2D arrays.
FY 1995 Determined intrinsic resonance structure in 2D arrays; Calculated stable phase-locking parameters in two-cell ladder array; Developed fabrication technology for array oscillators operating at a frequency of 300 gigahertz and emitting signals having milliwatts of power.
FY 1996 Project completed. Measure power and linewidth off-chip.

4. Develop pulse-programmable Josephson voltage standards (JVS)

FY 1995 Pulse-programmable JVS concept invented.
FY 1996 Pulse-programmable JVS demonstrated experimentally.
FY 1997 Use pulse-programmable JVS to synthesize sine waves at frequencies from one kilohertz to one megahertz.

Nanoscale Cryoelectronics

Project Leader: Richard L. Kautz

Staff: 8.0 Professionals, 1.0 Student

Funding level: $1.4 M

Funding sources: NIST and OMP (42%), Other Government Agencies (58%)

Objective: Develop ultra-small electronic devices operated at cryogenic temperatures for applications in fundamental metrology and industrial instrumentation.

Background: Electronic devices operated at the reduced noise levels afforded by cryogenic temperatures offer the ultimate in measurement accuracy and sensitivity. The goal of Nanoscale Cryoelectronics is to exploit this benefit of low temperatures and use microcircuit technology to develop new devices for fundamental metrology and industrial instrumentation. This project presently focuses on two such devices: an electron pump capable of counting electrons one-by-one and an x-ray detector that senses the temperature rise of electrons in a metallic x-ray absorber. The electron pump, based on ultra-small tunnel junctions, can accurately transfer a specified number of electrons to a capacitor. The pump will provide the basis for a new fundamental standard of capacitance and may lead to an improved measurement of the fine structure constant. The hot-electron x-ray detector achieves better energy resolution than conventional detectors without sacrificing either detection area or response time, and promises rapid commercial introduction in x-ray materials-analysis systems.

Current Tasks:

1. Develop single-electron pump for metrological applications

FY 1991	NIST Competence funding received for the first of five years to support the development of an accurate electron pump.
FY 1992	Error rate of electron pump analyzed theoretically and shown to require at least five tunnel junctions for metrological accuracy. Single-electron transistors required for testing pump performance fabricated, tested, and shown to be of adequate noise performance.
FY 1993	Five-junction electron pump fabricated and tested. Effect of environmental noise on pump accuracy investigated theoretically.
FY 1994	Experimental results on the five-junction pump were published, demonstrating an accuracy of 0.5 part per million.
FY 1995	Seven-junction pump designed, fabricated, and underwent preliminary testing.
FY 1996	Demonstrated a seven-junction pump with an accuracy of 15 parts per billion and an average time of 10 minutes between leakage events in the hold mode.
FY 1997	As a first step toward building a capacitance standard, use an electron pump to charge an external capacitor; Begin detailed experimental investigation of error mechanisms in the electron pump.

FY 1998 Develop electron pumps for use in a capacitance standard to be built by the Electricity Division.

2. Develop hot-electron microcalorimeters as x-ray detectors

FY 1994 Microcalorimeter based on sensing temperature of electrons in a metallic absorber near 100 millikelvin was conceived, fabricated, and tested, to demonstrate an energy resolution of 22 electron volts at 6 kiloelectron volts, an order of magnitude improvement over conventional detectors; Achieved a sensitivity of 3 x 10-13 W/Hz^{½}, the best ever recorded for a bolometric device.

FY 1995 Detectors with large area (0.25 mm^2) and fast response time (10 microseconds) demonstrated, using a normal-insulator-superconductor tunnel junction thermometer and a superconducting transition-edge thermometer operated with electrothermal feedback; Achieved an energy resolution of 0.2 electron volts for a small-area detector responding to a heat pulse, the best resolution ever obtained in any calorimetric technology.

FY 1996 Demonstrated an x-ray microcalorimeter with an energy resolution of 8 electron volts at 6 kiloelectron volts and a count rate of 100 counts per second; Obtained NASA funding to work toward an energy resolution of 2 electron volts for x-ray astronomy over three years.

FY 1997 Develop an x-ray microcalorimeter with 5 electron volt energy resolution; Optimize microcalorimeter to achieve a count rate of 250 counts per second.

FY 1998 Demonstrate a microcalorimeter with a count rate of 1000 counts per second at an energy resolution of 5 eV.

FY 1999 Design, build, and test a 2 by 2 array of x-ray microcalorimeters as a demonstration of their potential for astronomical applications; Fabricate a microcalorimeter with 2 electron volt resolution.

3. Develop practical hot-electron x-ray system for microanalysis applications

FY 1995 Design, fabricate, and test cryostat with an adiabatic demagnetization refrigerator (ADR) to achieve an operating temperature of 80 millikelvin directly from a helium bath which nominally operates at a temperature of 4 kelvin (or 4000 millikelvin).

FY 1996 Fabricated and tested a complete x-ray system, including adiabatic demagnetization refrigerator, SQUID preamplifier, and superconducting transition-edge microcalorimeter; Interfaced system to an electron microscope and demonstrated 8 electron volt resolution in x-ray fluorescence spectra.

FY 1997 Fabricate improved adiabatic demagnetization refrigerator and cryostat; Determine utility of a capillary x-ray lens to increase collection efficiency; Evaluate detectivity of system for trace element analysis.

FY 1998 Deliver complete x-ray system, including cryostat, adiabatic demagnetization refrigerator, and transition-edge microcalorimeter to the Surface and Microanalysis Science Division.

High-T_c Electronics

Project Leader: David A. Rudman

Staff: 4.25 Professionals, 1.0 Guest Researcher, 1.0 Postdoc, 1.0 Students, 0.25 Technician

Funding level: $0.9 M

Funding sources: NIST (42%), Other Government Agencies (58%)

Objective: Use the unique properties of high-temperature superconductors to develop new devices and electronics for measurements and standards for the electronics industry. Develop new measurement techniques, devices, and circuits in support of the emerging superconducting electronics industry.

Background: High-temperature superconductivity (HTS) has opened the possibility for operating superconducting electronic instrumentation at temperatures accessible with present-day cryocoolers. Low-temperature superconductors have already been used to produce unique standards, such as the Josephson volt, and measurement apparatus, such as Superconducting Quantum Interference Devices. Equivalent HTS devices would expand the applicability of these devices far beyond standards and research laboratories. Thus the primary "customer" for the devices being developed by this project are the other NIST divisions responsible for standards and measurement techniques in areas such as the volt, and infrared, terahertz, and microwave radiation. The project will also provide support for the emerging HTS superconducting electronics industry, both through measurements and through the development of HTS devices and circuits.

Current Tasks:

1. Develop microwave testing for unpatterned HTS films (Collaboration with EEEL Electromagnetic Fields Division)

FY 1992	Collaborated with University of Colorado on measurement of microwave surface resistance (R_s) of HTS films using parallel plate resonator.
FY 1993	Implemented dielectric cavity resonator technique for R_s measurements. Obtained significant improvement in measurement reproducibility. Developed novel technique to measure microwave properties of tunable thin film capacitors at cryogenic temperatures (with University of Colorado).
FY 1994	Refined dielectric resonator technique. Compared results at different frequencies. Measured microwave properties of tunable capacitors made from strontium titanate at cryogenic temperatures (76 kelvin and 4 kelvin).
FY 1995	Extended dielectric resonator technique to measure power dependence of R_s using pulsed microwave approach to avoid sample heating. Began industrial collaboration to improve and use measurement technique.

FY 1996	Improved R_s and power handling measurements; With industrial collaborators, compared cavity resonator measurements to other techniques; Transferred cavity technique to interested parties.
FY 1997	Refine R_s and power handling measurement capability using dielectric-loaded cavity resonator; Implement program to model fields in cavity; Construct larger cavities to handle full 75 millimeter wafers.

2. Characterize microwave performance of HTS films

FY 1995	Measured dependence of low-power R_s on film thickness.
FY 1996	Began study of R_s as a function of film processing parameters, using films made at NIST and from industrial collaborators.
FY 1997	Continue to study microwave performance of HTS films; Seek correlations with film microstructure and dc electrical properties; Compare performance of unpatterned films with patterned devices; Provide industry with guidance to understanding and improving performance.
FY 1998	Evaluate microwave performance of full wafers from a variety of manufacturers.

3. Develop cryogenic microwave device measurement capabilities (with EEEL Electromagnetic Fields Division)

FY 1993	Fabricated and measured the first thin-film tunable resonator, operating at a frequency of 5 gigahertz, made from HTS films and an electrically adjustable thin film capacitor, in collaboration with University of Colorado.
FY 1994	Developed cryogenic microwave test fixture and probe for testing HTS devices. Modified NIST calibration software (DEEMBED) for use with superconducting calibration standards to perform calibrated on-chip measurements. Performed calibrated measurements on tunable thin-film superconductor-ferroelectric microwave transmission lines and resonators.
FY 1995	Compared performance of HTS microwave devices patterned by different techniques (in collaboration with other laboratories). Completed procurement for cryogenic microwave probe station.
FY 1996	Developed techniques for calibrated cryogenic microwave probing of superconducting devices; Used probe station to improve measurements of HTS devices patterned by different techniques.
FY 1997	Compare performance of patterned HTS devices to unpatterned films; Investigate effects of patterning damage on HTS devices; Provide industry with measurement support for cryogenic microwave devices using probe station.
FY 1998	Develop measurements of third-harmonic generation and intermodulation products in HTS devices as a function of microwave power.

4. Develop HTS Josephson junction technology for measurements and standards applications

FY 1991	Developed superconductor-normal metal-superconductor (SNS) Josephson junctions using HTS films.
FY 1992	Improved SNS junction fabrication process; Confirmed that devices behave as predicted by standard models.
FY 1993	Developed technique to increase resistance of the fabricated junctions; Coupled junctions to far infrared laser using lithographed antenna and

measured response of the junctions up to the highest frequency that such junctions had ever been operated (8 terahertz); Fabricated world's first HTS SNS junctions and Superconducting Quantum Interference Devices (SQUIDs) over HTS ground plane; Demonstrated phase locking between two HTS junctions at frequencies up to 1.06 terahertz and temperatures up to 35 kelvin.

FY 1994 Measured heterodyne mixing products from HTS junctions at frequencies as high as 30 terahertz, with difference frequencies up to 27 gigahertz (in collaboration with other Groups); Demonstrated that HTS junctions produce sufficiently large steps at a temperature of 38 kelvin and a frequency of 62 gigahertz for use in programmable voltage circuits.

FY 1995 Determined that microwave-induced Shapiro steps in these junctions flat to approximately 5 parts per million at a temperature of 4 kelvin and 100 parts per million at 76 kelvin (both numbers measurement limited), indicating junctions may be appropriate for voltage standard applications; Demonstrated resonant phase-locking scheme for HTS arrays for use as millimeter-wave sources; Developed first SNS junctions on silicon substrates (in collaboration with a U.S. company).

FY 1996 Tested alternative junction technology (bicrystals) for application to voltage standards and other measurements; Fabricated first bicrystal junctions on sapphire substrates; Developed novel multilayer process for HTS circuits.

FY 1997 Complete study of junctions on sapphire bicrystals; Complete demonstration of multilayer circuit fabrication; End task.

5. Develop HTS bolometers as improved radiometers

FY 1994 Fabricated first HTS antenna-coupled microbolometers using thermally-isolated yttria-stabilized zirconia membranes on silicon substrates. Devices were the lowest noise, fastest liquid-nitrogen-cooled detectors ever.

FY 1995 Developed process to fabricate large-area HTS films on silicon membranes. Device geometry suitable for electrical-substitution radiometer.

FY 1996 Measured electrical noise in HTS films at transition temperature on different substrates, including silicon; Noise approached the Johnson limit, verifying that films are appropriate for thermometer applications (with U.S. companies).

FY 1997 Fabricate HTS films on large-area silicon membranes; Test for use in electrical substitution radiometers (same collaborations).

FY 1998 Fabricate prototype electrical-substitution radiometer using HTS transition-edge thermometer (same collaborations).

6. Develop micromachined ion traps (with Physics Laboratory's Time and Frequency Division)

FY 1996 Developed initial design to test micromachining concepts for ion trap fabrication; Selected laser cutting as most appropriate initial approach for substrate machining.

FY 1997 Fabricate and assemble first micromachined ion traps; After testing (by Time and Frequency Division), iterate on design.

Superconductor Standards and Technology

Project Leader: Loren F. Goodrich

Staff: 1.0 Professional, 1.0 Students, 1.0 Technician

Funding level: $0.4 M

Funding sources: NIST (85%), Other Government Agencies (6%), Other (9%)

Objective: Provide standards, measurement techniques, quality assurance, reference data, and issue clarification for both high- and low-temperature superconducting wire technology in support of applications involving U.S. industry such as magnetic resonance imaging, and development of laboratory magnets, fault current limiters, magnetic energy storage devices, motors, generators, and transmission lines.

Background: The project is internationally recognized as the leader in the development of standards for critical-current measurements and is leading the international effort for all superconductor standards. This effort is vital to U.S. industry, which now concentrates on conventional low-temperature superconductor (LTS) materials. This effort will become more vital to U.S. industry as additional new applications that use high-temperature superconductors (HTS) are commercialized. One of the most important performance parameters for large-scale applications is the critical current, I_c, of a superconductor, which is the current level that under given conditions, marks the transition between the superconducting state and the normal state. The critical current is difficult to measure correctly and accurately, and these measurements are often subject to scrutiny and debate. This is especially true for measurements on HTS.

Current Tasks:

1. Develop international standards for superconductors

FY 1989	International Electrotechnical Commission (IEC) Council established Technical Committee, TC 90, to create international standards for superconductivity.
FY 1990	First technical committee meeting held; two Working Groups formed. First working group meeting held; Goodrich became U.S. Technical Advisor to TC 90.
FY 1991	Working group meeting in Boulder; Goodrich became the Convener of Working Group 2 and drafted the first IEC standard test method.
FY 1992	Working Groups 1 and 2 draft documents were reviewed; a third working group was formed.
FY 1993	Five New Working Item Proposals were considered; chief architects assigned to each of these.
FY 1994	Japanese National Committee (JNC) created the first draft of three of the five proposals; Goodrich became Chairman of TC 90.

FY 1995	Working group meeting held to advance draft documents; Meetings were held to discuss the status and existing Committee Drafts.
FY 1996	Worked on draft documents from Working Groups 1, 2, 4, 6, and 7; Approved Committee draft for voting from Working Group 2.
FY 1997	Meetings held in China in October 1996; circulate, discuss, and edit documents from Working Groups 1, 2, 4, 5, 6, and 7; vote on draft international standard from Working Group 2.

2. Develop metrology for I_c measurements on HTS

FY 1993	Technical Working Area (TWA) "Characterization and Evaluation of High-Temperature Oxide Superconductors" proposed at meeting of Versailles Project on Advanced Materials and Standards (VAMAS).
FY 1994	Started separate interlaboratory comparisons of I_c measurements on HTS samples in U.S., Europe, and Japan. Two samples from U.S. industry were used.
FY 1995	Reported preliminary results of U.S. comparison, the first successful comparison of I_c on HTS; measurements in U.S. comparison completed and final report started.
FY 1996	Completed final report on U.S. comparison; Completed comparison in Europe; Planned comparison in Japan; Planned second stage international comparison.
FY 1997	Report comparison in China in October 1996, to confirm the results from the U.S. comparison; Conduct second stage interlaboratory comparison.
FY 1998	Analyze results from second stage and draft set of guidelines for measurement of I_c in HTS materials; Complete construction and testing of high-current, variable temperature, I_c measurement system.

3. Develop metrology for I_c measurements on LTS

FY 1986	VAMAS established technical working area on superconducting and cryogenic structural materials.
FY 1987-88	First international interlaboratory comparison of I_c measurements started; Three samples were used, one each from Europe, Japan, and USA; NIST discovered significant source of variation in measurements.
FY 1989	NIST asked to draft a test procedure for second comparison.
FY 1990,91,92	Second comparison started and continued, using NIST procedure; a NIST Standard Reference Material and a wire sample were used.
FY 1993	Final report on VAMAS comparison started.
FY 1994	NIST helped establish standard I_c measurement technique for superconducting wire for International Thermonuclear Experimental Reactor (ITER); Participated in and reported on the first ITER interlaboratory comparison of niobium tin compound $(Nb_3Sn)I_c$ measurements.
FY 1995	U.S. procedure used in a second ITER interlaboratory comparison. Conducted comparisons with members of the ITER U.S. Home Team to determine the accuracy of I_c measurements on superconducting wires and assist them in reducing their uncertainties; Produced a 1-hour training video.
FY 1996	Created an accurate database of magnetic field and confirmed capability to measure I_c at 12 T with current pulses and temperature dependence of I_c up to temperatures of 5.0 kelvin in liquid helium.

FY 1997 Develop I_c measurement capability up to 100 amperes in helium gas over the temperature range of 5 to 10 kelvin to determine the temperature stability margin for ITER and magnets that operate near 10 kelvin; Create database for the temperature stability margin of Nb_3Sn wires; Study effect of sample coil diameter on the measured I_c.

FY 1998 Create database for the temperature stability margin of niobium titanium alloy and niobium aluminum (Nb_3Al) wires.

4. Develop metrology for sensitive low-temperature measurements

FY 1989 Developed first passive I_c simulator based on earlier NIST active simulator; new design is sample-substitution box which can be used to compare dc and pulse techniques for measuring I_c in HTS.

FY 1990 Direct comparison made of steady state and pulse techniques on HTS samples and an I_c simulator.

FY 1991 Developed new active simulator with I_c selectable from one thousandth of an ampere to 10,000 amperes; first 50-ampere I_c simulator built and used in an interlaboratory comparison.

FY 1992 Developed hybrid simulator which is easier to calibrate; Conducted a simulator comparison with two other U.S. labs; Developed high-current (100-300 ampere) pressure contacts to HTS tapes; Began design and construction of a high-current variable temperature cryostat.

FY 1993 Participated in VAMAS interlaboratory comparison of critical magnetic fields, using SRM-1457 to check magnetic field calibrations among 11 laboratories; Designed custom simulator of high mutual inductance to simulate coils; Started preliminary testing of high-current variable temperature cryostat.

FY 1994 Made transport residual resistivity ratio measurements on high purity aluminum bars to compare with eddy current decay method. Conducted a simulator interlaboratory comparison with 12 U.S. laboratories.

FY 1995 Developed a custom simulator for a U.S. company; Made transport magnetoresistivity measurements on high purity aluminum and copper bars to compare with eddy current decay method.

FY 1996 Finished fabrication and testing of custom simulator; Loaned I_c simulators to two U.S. laboratories; Developed and verified capability to acquire voltage-current characteristics using variable-duration current pulses.

FY 1997 Develop capability to measure residual resistivity ratio of niobium-titanium wires; Develop capability of delivering 5000 current pulses to sample in a 12 T magnetic field to study fatigue due to Lorentz force cycling.